AUTOMAIN

Augmented Usage of Track by Optimization of Maintenance, Allocation and Inspection of Railway Networks

Project Reference: 265722
Research Area: SST.2010.5.2-1

Task 3.1: Inspection of track from in-service freight trains

Deliverable Reference No: D3.1

Dissemination Level		
PU	Public	

Document Summary Sheet

Additional Information	
Subproject / Work Package:	WP 3
Authors:	Christian Linder, René Schenkendorf, Gunnar Baumann
Participants:	
Document date:	20 December 2013
Status:	Draft

Changes

Draft 1	28th May 2013	Basic structure of the report created by Clive Roberts & Stephen Kent (UoB)
Draft 2	01th June 2013	Adaption of UoB template by Christian Linder (DLR)
Draft 3	16th July 2013	Completion of unaddressed items by René Schenkendorf (DLR)
Draft 4	3rd December 2013	Amendment by DB
Draft 5	13th December 2013	Integration of SIM and last review by DB
Draft 6	20th December 2013	Last changes after DB Review by Christian Linder (DLR)

Executive Summary

A defined condition of the track geometry is a prerequisite to ensure safety along the track and good rolling behaviour of the crossing vehicles. Thus, the condition monitoring of the track is of high relevance. By now, track inspections are carried out according to a predefined time interval strategy. In practice, special measurement vehicles are required to ensure highly precise data of the track geometry. In more detail, the data acquisition delivers a complete set of track geometry parameters which have to be evaluated for the purpose of maintenance management.

In general, the idea of track monitoring is to select certain informative parameters, e.g., the vertical alignment of the track, and to monitor these parameters over time. In doing so, track failures (e.g., isolated effects) become detectable and are addressed by an adequate maintenance intervention subsequently. However, to provide a more credible track monitoring program additional measurement data are mandatory which is contradicted by high operation costs of measurement trains. Hence, the idea is to use commercial trains like in-service freight trains for the purpose of data acquisition. They can be equipped with accelerometers which provide indirect information about the vertical alignment of the track. In this case, the track displacement can be calculated from acceleration data by double integration. The process of track displacement calculation is challenging by nature. Various problems associated with 1) the sensor hardware, 2) the numerical integration steps, and 3) signal filtering have to be addressed appropriately to get reasonable displacement and hence vertical alignment data.

The focus of WP 3.1 is to develop concepts to overcome these challenges. The additional effort needed for data processing increases the track maintenance efficiency substantially. For instance, the gathered data enable a continuous track monitoring, i.e., potential track failures become detectable at an early stage. Moreover, due to the increased number of data sets even a failure prediction can be put into operation. That is, the precursors of a track failure (tiny peaks in the displacement data) are evaluated to predict the remaining time until the expected track failure becomes critically. By knowing the remaining time until a track failure is expected an optimised maintenance can be scheduled.

In short, in WP 3.1 algorithms are derived which inform and support decision makers to manage the usage of maintenance resources and budget more efficiently.

Moreover, all calculated quantities which contribute to an improved maintenance management are stored into a railML file (see WP 5). Thus, a standardised exchange of information with third parties, e.g. WP 5 and WP 6, is possible.

TABLE OF CONTENTS

Figures

Tables

Glossary

SR_A	Alert limit - speed depend attention threshold for an economic maintenance used by DB
SR_{100}	Intervention limit - speed depend technical and economical threshold for maintenance used by DB
SR_{Lim}	Immediate action limit - speed depend limit threshold for safety reasons used DB
CSM	Common Safety Method

Introduction

The railways in Europe have to ensure high punctuality to fulfil the demands of their customers. On one hand, these are the passengers; on the other hand these demands are essential for freight to comply with today's industrial processes. Today's bottlenecks are in most cases malfunctions of signalling and speed restrictions in straight track. Hence, in this project the focus was on track alignment and switches & crossings. Especially the switch is a combination of signalling and track.

While D3.1 focused on the track and the track in switches, D3.2 worked in switches and single failures. But both monitoring and inspection technologies has to merged together to support the maintenance planning for the freight line. Figure 1 shows the two paths in the V-model.

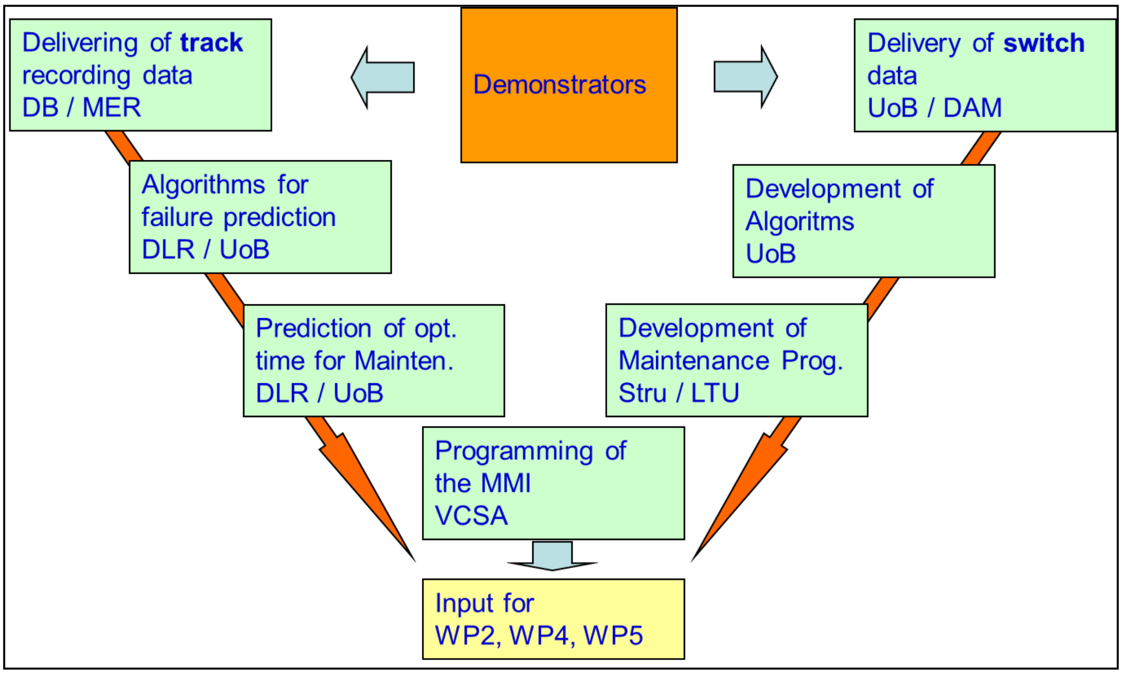

Figure 1 Workflow in WP3. The MMI merges the results together and works as a data hub.

From the history, the track and switch assessment was developed to enhance the safety of the railway operation. Based on experiences, today the assessment values were developed more and more by the use of verified simulation models. In most railways, the inspection interval is time based, and depends mainly on the maximum speed of the track.

If freight traffic is operated on a freight line the maximum speed is120km/h. Depending on the maximum speed of a line an inspection interval between 12 and 18 month is defined in the standards. After an inspection very often a lot of speed restrictions occur and maintenance has to be done rapidly after the measurements. This results in high costs for short-term orders and in track closures for possessions.

Here, the great advantages of a track monitoring will be obvious! Based on a numerous of measurements, no surprises after inspections occurs and a strategic maintenance planning will extend track life, track quality, track availability by steady or decreased costs.

A second advantage is the fact, that a continuous monitoring supports the CSM responsibility of modern railways.

The general idea of track monitoring is to select certain informative parameters, e.g., the vertical alignment of the track, and to monitor these parameters over time. In doing thius, track failures (e.g., isolated effects) become detectable and can be addressed by an adequate maintenance intervention strategy. However, to provide a more credible track monitoring program additional measurement data are mandatory which is contradicted by high operation costs of measurement trains.

Hence, the idea is to use commercial trains like in-service freight or passenger trains for the data acquisition. The trains can be equipped with accelerometers which provide indirect information about the vertical alignment of the track. Measuring the acceleration of the axle boxes, the track displacement can be calculated by double integration. The process of track displacement calculation is challenging by nature. Various problems associated with 1) the sensor hardware, 2) the numerical integration steps, and 3) signal filtering have to be addressed appropriately to get reasonable displacement and hence vertical alignment data.

This deliverable is organised as follows.

Sections 1 and 2 relate to the current inspection standards and technologies, respectively. For instance, national as well as European standards of track inspection are introduced shortly.

Section 3 reviews the utilised sensor and measurement concepts and explains the data pre-processing steps, i.e., the recalculation of displacement data by evaluating acceleration data.

Section 4 is dedicated to describe the algorithms implemented for the purpose of track failure prediction in more detail.

Section 5 addresses the development of an assessment tool and the concept of the man machine interface (MMI), respectively. Here, it is described how the results derived in WP 3.1 are linked to the associated work packages, e.g., WP 5 and WP 6.

Finally, the conclusions are given in Section 6.

1 Current Inspection Standards and Technologies

This chapter introduces the current state of the art in failure track monitoring and track quality assessment, respectively. Moreover, it is described how the need of maintenance activities is determined and which technologies are put into operation.

Maintenance of Railway Networks across Europe follows very distinct guidelines. As part of the consecutive harmonization process, collateral normative work is done on the European norm EN13848 which aggregates several national regulation standards to a new one on a European level.

To better demonstrate the motivation of the work done in this work package, a short introduction using the example of Germany's Railway Maintenance procedures is given. Subsequently, the European normative regulations are summarised as well. In general, these guidelines represent the latest inspection standards and are carried out across the networks each day.

To perform maintenance according to the regulations, methods and technologies like inspection vehicles need to be available. A short summary is given in Section 1.3. Section 1.4 describes what kind of data is collected and explains, why the vertical track alignment was chosen to be deeper investigated in this work package.

1.1 National Regulations

The "Deutsche Bahn" (DB) maintains its networks superstructure, rails and track geometry according to the principles of a company guideline named Ril821. This document defines a three-tier threshold system, which specifies three fixed values of maximum disturbance for each measurement parameter and speed. Those three values are called SR-values (germ. Störgröße/Reaktion = Disturbance/Reaction) and are ordered by raising criticality:

1. SR_A - Attention threshold for an economic maintenance
   when measurements reach that limit, it should be expected that maintenance is needed in the near future. Corresponding maintenance tasks need to be scheduled for optimal cost efficiency.

2. SR_{100} - Technical and economical threshold for maintenance
   this limit defines the threshold on which the track geometry has reached the maximum tolerable condition with which the rail operation can still be carried out without interference. Maintenance must to be carried out before the next interval based inspection.
   While there are no more inspections until the repair is done, it cannot be assured that the failure does not reach SR_{Lim} in the meantime.

3. SR_{Lim} – Limit threshold for safety reasons
   when track geometry measurement parameters reach or cross the SR_{Lim} values, it must be assumed that the functionality of track or superstructure is affected. Appropriate measures must be taken to ensure safety (mainly this results in a reduction of maximum speed). Maintenance must be carried out at earliest possible time.

Some of the parameters measured according to Ril821 are vertical level, twist, deviation and gauge. While this report focusses on the work done on analysing failures in vertical level Table 1 summarizes the limit values given in millimetre.

Table 1: Thresholds for vertical alignment extracted from Ril821. Here v means the train speed in km/h.

Thresholds for vertical alignment extracted from Ril821.	Unit	v < 80	80 < v < 120	120 < v < 160	160 < v < 230	v > 230
SR_A	[mm]	12	10	8	6	5
SR_{100}	[mm]	15	13	11	9	7
SR_{Lim}	[mm]	21	17	14	11	9

1.2 European Standard EN13848

In contrast to national regulations, there is a norm that aims to align the trans-European maintenance specification and their common core. Therefore, it has also a three-tier limit value system, with very similar meaning to the German one. There is an Alert Limit, Intervention Limit and the Immediate Action Limit.

One of the main differences compared to the German one is, that the scoring of a failure along the track is done in three wavelength bands. The norm separates failures by wavelengths of 3m – 25m (D1), 25m – 70m (D2) and 70m – 150m (D3).

Table 2 shows the mean to peak values in millimetre given by En13848 for each wavelength band. Wavelength band D3 is not applicable for isolated defects, i.e., to detect single peaks in the displacement data.

Table 2: Threshold limits extracted from EN13848.

	Mean to Peak [mm]	
Speed [km/h]	**D1**	**D2**
v < 80	28	N/A
80 < v < 120	26	N/A
120 < v < 160	23	N/A
160 < v < 230	20	33
v > 230	16	28

To ensure the comparability of the results shown in this report, the data used as input for the algorithms are pre-processed to derive base data according to the German guidelines as well as for the EN13848 referenced in 3.4.

1.3 Measurement trains, current inspection technologies

Up today there are various measurement trains for different issues in use. These trains use different measurement technologies and, that's important, different assessment methodologies. A comparison of the countries is nearly impossible.
First attempts for unification were done in the EU-Project DynoTrain, an assessment of methodologies was developed and published in EN13848. Up to now, no infrastructure company use these values and assessments in daily inspection. Because all railways have a safe operation, a harmonization will occur slowly. Regarding the economics of maintenance, big cost savings are possible by using new measurement technologies and assessment criteria.

Today five types of measurement trains are in use at Deutsche Bahn:

- Clearance outline measurement train LIMEZ
- Catenary inspection train
- US- and ET-Inspection train
- Determining the running behaviour of the vehicle with ICE-S and tilting trains with VT612.9
- Track geometry inspection with GMTZ and Railab Mark I/Railab Mark II

Automain focus on the track geometry because a large amount of maintenance costs is related to tamping. The traditional measurement method in DB was the three-point versine measurement. Based on that measurement method, the assessment criteria were defined. A great disadvantage of three-point measurements is the fact, that the related transfer function has roots and is not linear. This implies problems inverting this function and leads depending on the wavelength to an over- or underestimation of measured track geometry failures.

All inspection trains since Railab I have modern inertial measurement platforms with gyroscopes, which are able to measure the true geometry. But because of the assessment system, these measurements will be calculated back to three-point versine measurements. If the new, by DB Netz developed, assessment system will be accepted by the railway authority EBA in the future, a comparable assessment like EN 13848 will be possible.

One of the advantages of a continuous track monitoring is the possibility of threshold prediction. During today's maintenance, after an inspection a lot of several work items has to be planned. The average preliminary lead time varies between 5 and 1 year. Larger possession times have to be early fixed to integrate occurring delays into the train schedules. With those procedure customers, logistic companies as well as individual passengers, get a better certainty of their planning. It's a paradigm change, to start a maintenance planning independent of inspection results!

1.4 Failure Types of special interest

For the maintenance (restoring) of the track geometry several types of tamping machines are available. For short failures with a defect length of a few meters single failure tamping machine like Sprinter are used. But this type of machine is not able to tamp longer section with the required quality. For longer sections two three or four sleeper tamping machines are used. These machines are able to tamp up to 2200 m per hour. A good planing of maintenance activities is necessary to utilize the full potentials of these machines.

A precise prediction of track degradation, combining of sections for maintenance and selection of appropriate tamping machines leads to low maintenance cost and minimal possession time

Detailed analyses of track geometry measurements clearly show that the need for tamping /restoring of track geometry is often triggered by single failures. This makes a mid- and long-term planning of the maintenance activities more difficult. Existing measurements are basing on three point signals and the accuracy with respect to the location does not allow a good prediction of the track degradation.

This fact together with the inspection strategy described in the chapter Introduction is the reason why continuous track monitoring can noticeable improve the planning and scheduling of maintenance.

2 Inspection of the track in switches and crossings

During the last periods in European projects, almost all projects have done a separation between straight track and the switches and crossings. None of these projects has taken it into account, that the inspection of the track in S&C is total different and also connected to high costs for inspection and maintenance.

In Automain, we closed that gap by an automatic switch inspection (track) vehicle. That step was necessary due to the availability of large freight stations for a undisturbed operation.

Usually the track has to be closed for inspection. In DB, a so called PRINS-Team, two electrical and one track engineer inspected the track. They are always being able to do minor maintenance and service.

For safety reasons, the measurement of the track gauge in front of the switch, in the crossing and behind has to be measured accurately. This work is usually done with small trolleys. During one day, approx. 4-6 switches can be inspected. The track has to be closed for the inspection.

2.1 Use of SIM measurement vehicle

During the last 10 years, large developments were done to minimize laser measurement systems. One of these systems is shown in Figure 2.

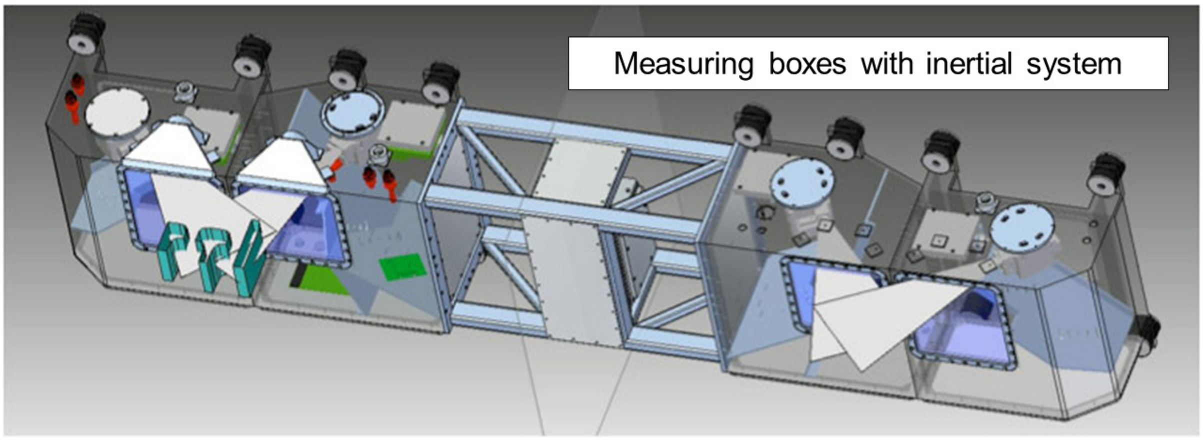

Figure 2: Measuring boxes with inertial system developed by Santanera/DMA.

The measurement system is based on the triangulation method. In this, the route travelled is determined by the laser spot, the reflection of which is monitored by the camera. The distance between camera and object can then be calculated from this.

The measuring system was already installed on a SIM-Multipurpose-Car of Strukton/Eurailscout. For the further development the SIM was used in the Automain project. For the measurements a GAF of DB was used as Steering Car.

Figure 3: SIM-Multipurpose-Car by Strukton/Eurailscout including the laser-system.

Figure 4: Operation in the DB network with a GAF as Steering Car.

2.2 Results of the demonstrator

In the demonstrator, the measurements were done up to 40 km/h. During the preparation of the measurement, a “screenplay” for the SIM was written. This screenplay was fitted into the regular schedule for the station. The screenplay was handed to the traffic controller.
With that preparation it was possible to inspect 100 up to 150 switches within one night shift (7 hrs), demonstrated in Nürnberg and Rosenheim.

For the identification of each unique switch/frog, two ways of referencing were tested:

- geo-referencing by GPS
- map-mapping, supported by GPS
- RFID tags on each frog

During the inspection runs it was found, that geo-referencing with GPS was absolutely unsuitable. The map-mapping was done after the inspection shift. it works well, but an online information, which switches were tested is much better. It allows minor corrections during the inspection shift. In the demonstrator we got the experience, that the traffic controller differs sometimes from the screenplay because of delayed freight trains or other reasons.

Best results we have obtained by RFIDs. The frogs in Nürnberg were tagged with intermetic RFIDs which can be read out up to 100 km/h passing speed.

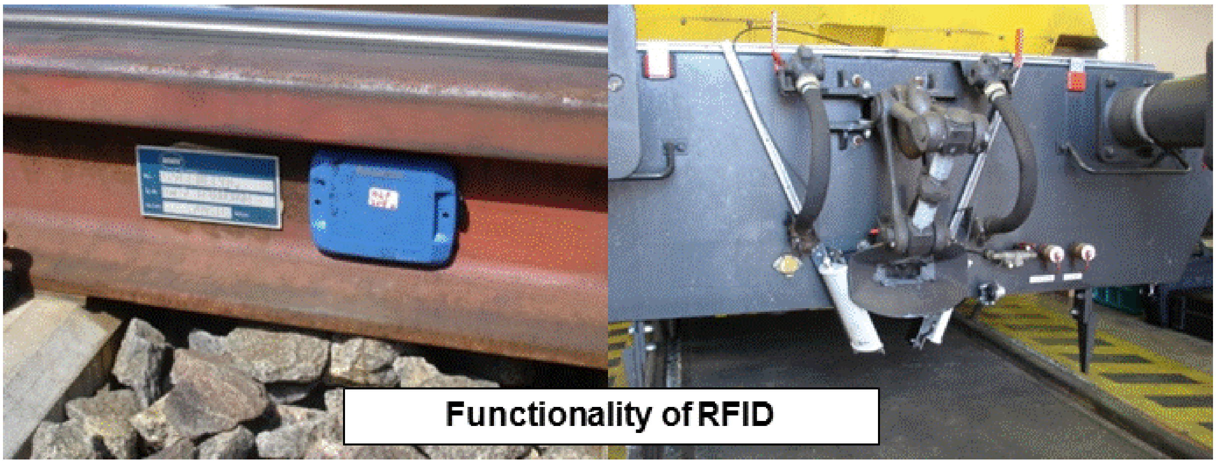

Figure 5: left: blue RFIDs glued on the frogs; right: RFID-antenna in front of the SIM.

An appropriate inspection speed is 40 km/h , a scan of the track profile is made every 20 mm. For the general assessment of the whole switch a top view pattern is compiled. A horizontal cross-section is made on the profiles on 14 mm under the track upper edge.

The following figures demonstrate the process of image development and the calculation of the necessary data for the inspection. At the end of that process, the results must be comparable with the basic rules of switch inspection.

One major point of deviation is the fact that the new measurement was done under loaded conditions (SIM-Car), so the results are not comparable with unloaded measurements with a trolley. Especially the gauge differs of about 2mm on switches with wooden sleepers!

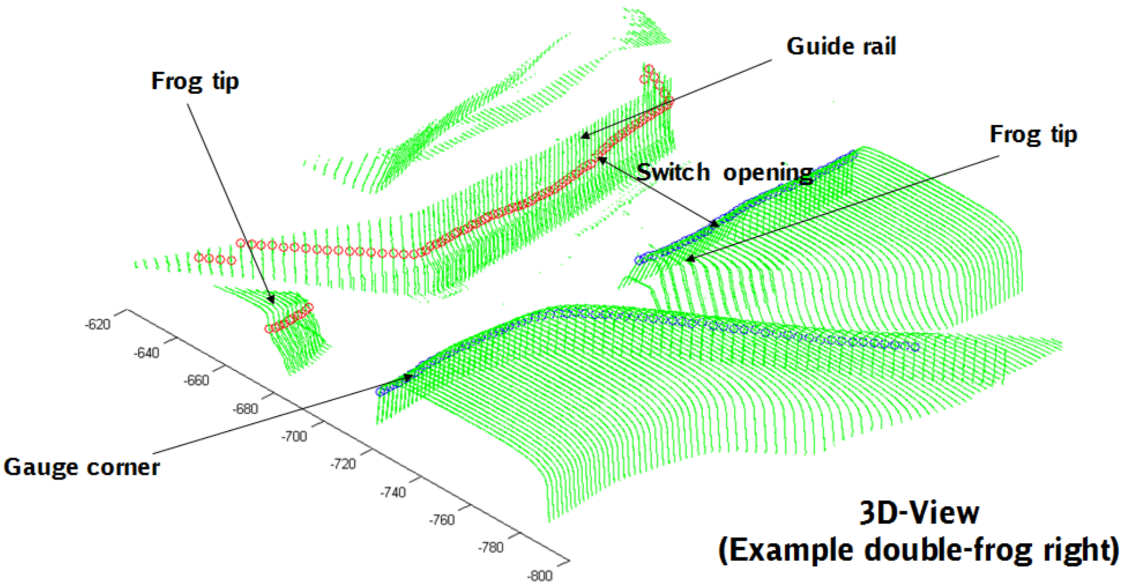

Figure 6: Cross-sections with a distance of 20mm in the most interesting area of the frog

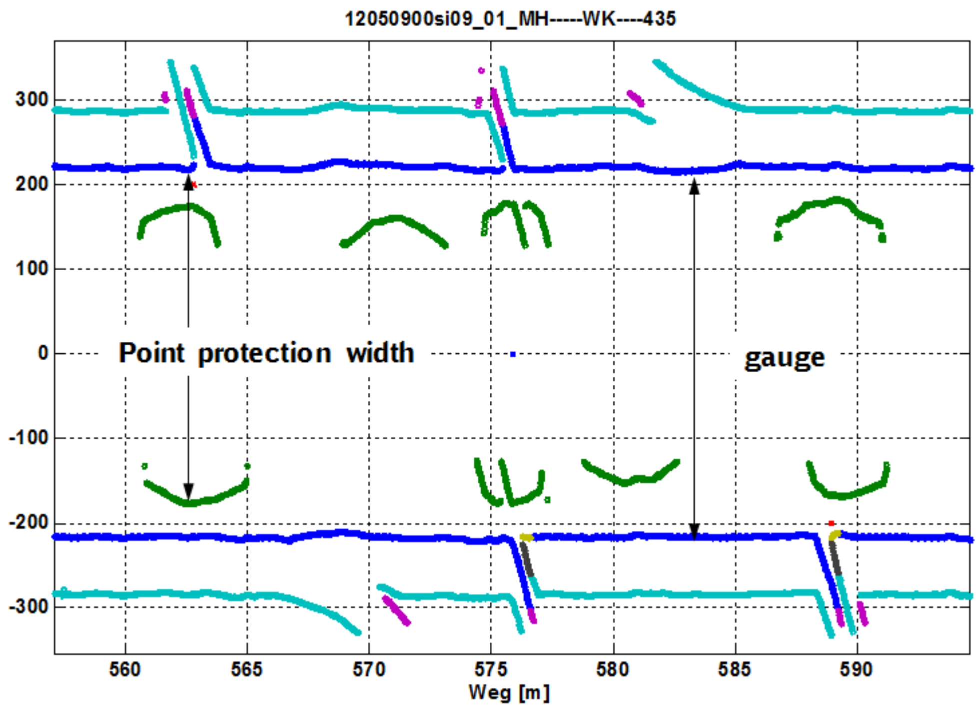

Figure 7: Automated identification of the 14mm point for the calculation of the inspection parameters, e.g. the gauge.

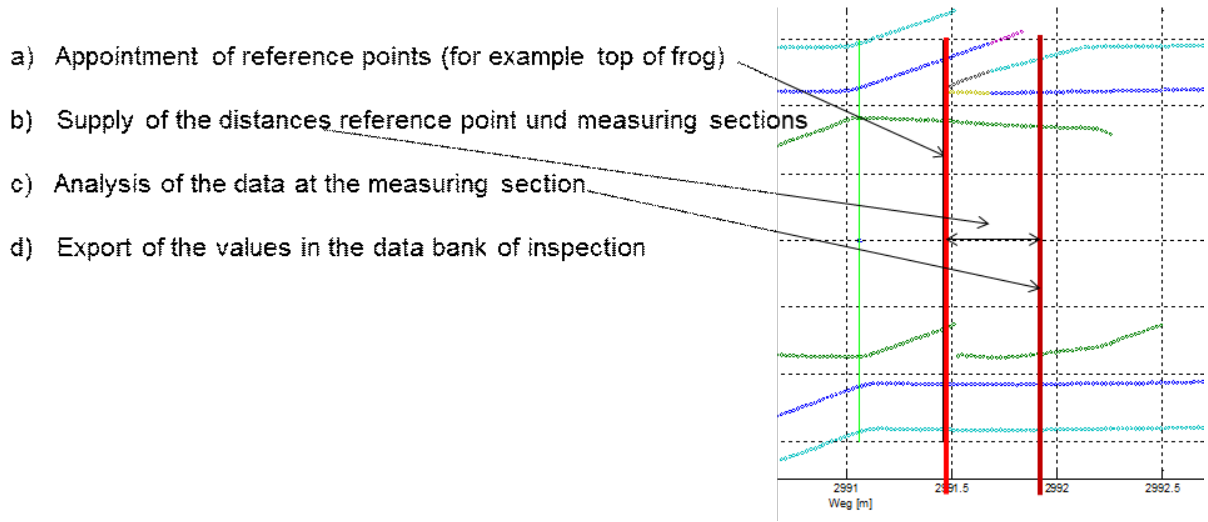

Figure 8: Correlation to the measuring sections of the basic rules.

Up to now, the calculation and reporting of the following values are part of the post-processing:

- gauge
- point protection width
- groove width

- Groove depth
- Elevation
- Right of way (start/ end emergency entry)

Planed or possible in the future are:

- Check of the switch tongues (check gauge 1,…..)
- Horizontal/vertical wear of the measured profiles
- alignment

The next figure shows the analysis of the differences between unloaded and loaded switch. For the statistics all measured switches in Nurnberg were taken into account.

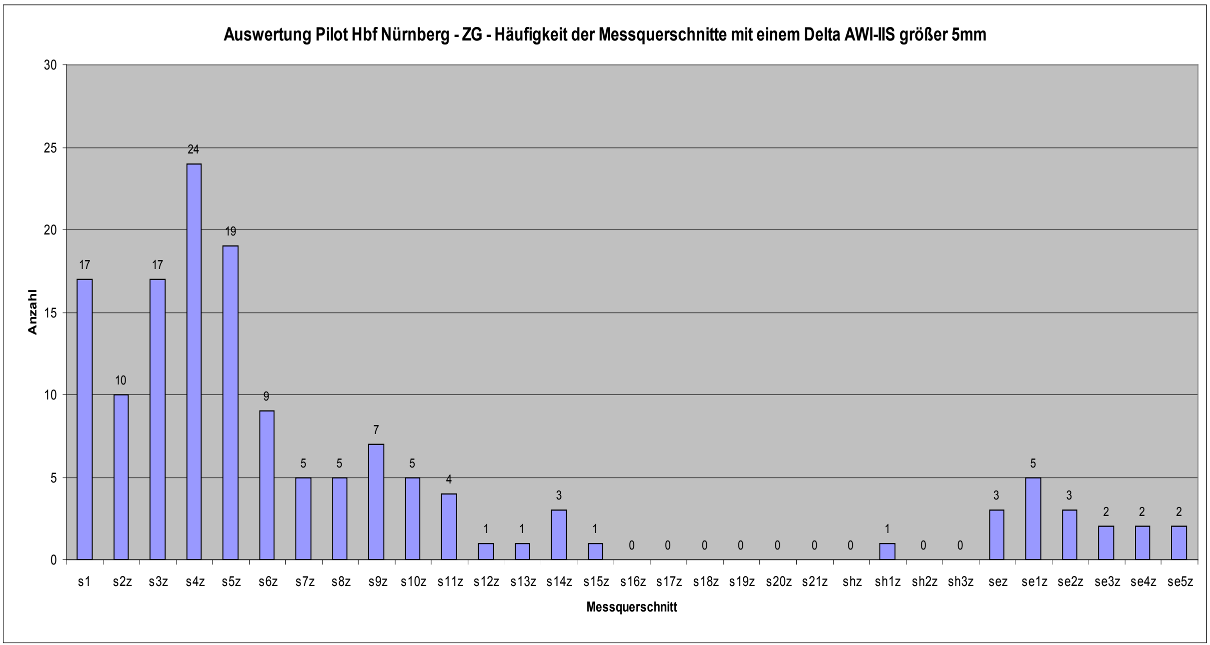

Figure 9: Largest differences between loaded and unloaded measurements positioned in the unfixed area of the switch blades (double track view).

To be sure, that the measured differences loaded/unloaded are not a result of a bad aligned laser system, a test of the repeatability was done, comparable with the requirements for the homologation of an inspection system.

Table 3: Confirmation of the repeatability of the laser measuring system.

Value	Standard deviation
Gauge	0.14 mm
Cant	0.36 mm
Opposite level	0.13 mm
Longitudinal alignment	0.59 mm
Lateral alignment	0.70 mm

Summarized it was proven that die laser measuring system, combined with the calculation and assessment algorithms, is suitable for a high-speed inspection of switches in stations. Especially in combination with freight lines the optimisation of inspection time and operation restrains is possible.

Next steps to be done are the discussions with the railway authorities on the thresholds of the inspection limits (loaded/unloaded) and the development of efficient maintenance processes. While in the past 2-3 repairs per day were necessary and feasible, so now we get approx. 30 - to 40 repairs, depending of the station size.

3 Inspection of track by in-service trains

3.1 Sensor and measurement concept

The sensor and the measurement concepts are described in more detail in WP 6. The major challenge is to minimize the risk for mechanical (gear) and electro-magnetic disturbances in a powered bogy by design.

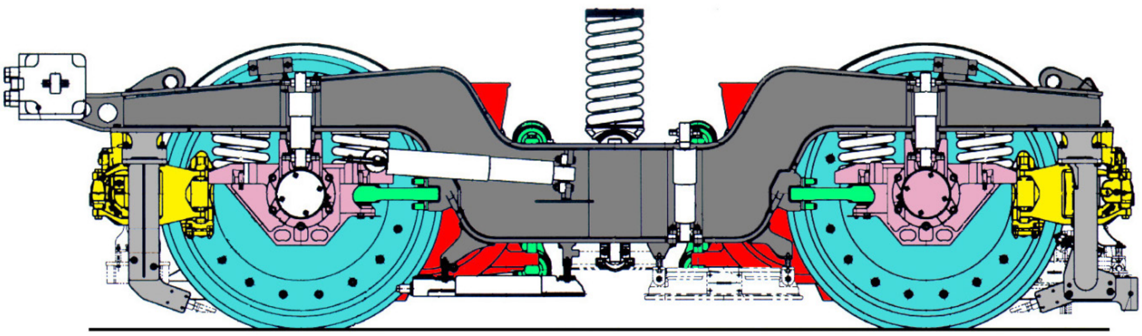

Figure 10: Schematic drawing of the powered bogy of the locomotive 189.

Beside these technical aspects, which have a big impact on the design, the second challenge is to measure the position of the train with high accuracy and repeatability. In the concept three different additional sensors are integrated to provide direct or indirect information that can be used for the calculation of the position:

- Differential GPS
- Speed sensor at one axle and
- Gyroscope (IMU).

Together with the acceleration signals itself, which contains unique pattern from switches and crossings, rail welds or other single effects, a good correlation of the different measurements should be achievable by a computer program.

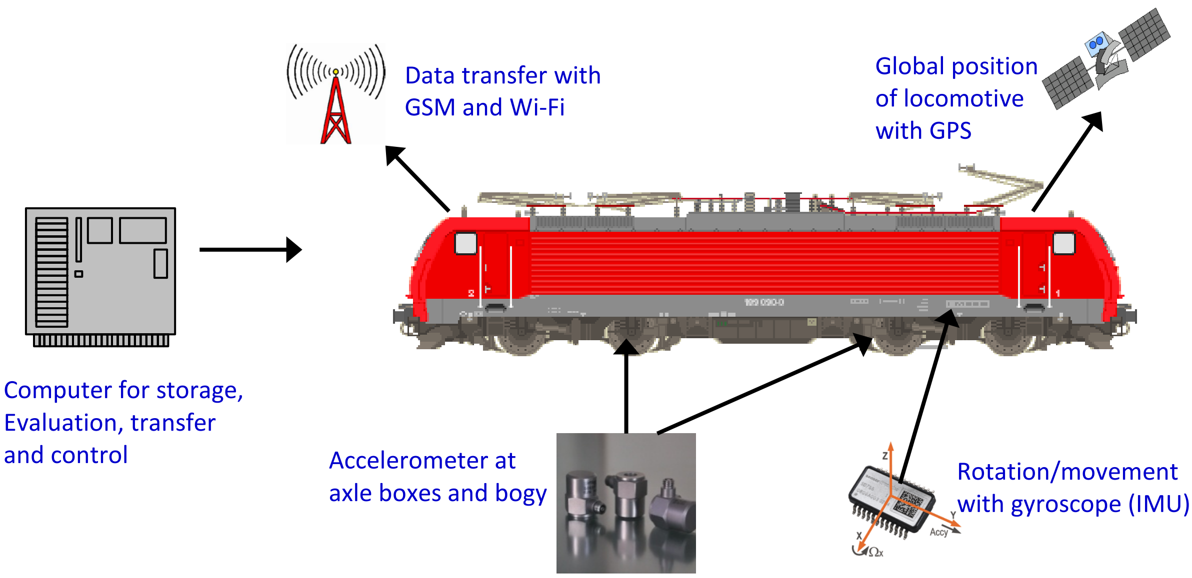

Figure 11: Schematic drawing of the measurement concept and used sensor.

At the axle boxes the acceleration in vertical and horizontal direction will be measured at two different sampling rates. The low sampling rate of 4 kHz is sufficient to identify track geometry defects in the relevant range of wavelengths. The sensors with a sampling rate of 20 kHz provide high frequency signals that can be used for the measurements of defects in the rail surface.

3.2 Data pre-processing

In this Section, the overall workflow of displacement recalculation is described. The process starts with the raw acceleration data. In a first step these data have to be converted into Matlab™ files. Subsequently, they can be transformed into displacement data for further interpretation.

3.3 Raw data process

The measurement signals will be pre-processed by hardware filters like anti-aliasing or high and low pass filters. These special designed filters guarantee a high quality of the raw signals. The raw data of all sensors will be stored in a database. For the transfer of data the different accelerations and the data from the IMU, GPS and speed sensor will be stored in files in binary format. Beside the data files a report file is available that contains errors of the system detected during the measurement run.

3.4 Data preparation for use in failure prediction algorithms

The very first step in the data driven track monitoring framework is to recalculate the track displacement by given acceleration data. From a pure mathematical point of view, the acceleration data have to be integrated twice to provide the displacement of the equipped axle box that is directly related to the track geometry. In practice, however, these two integration steps might cause serious troubles:

1) A proper sampling frequency is obligatory (at least two times above the Nyquest rate). Otherwise, artefacts are detected and analysed but no track features.

2) A credible numerical integration technique has to be applied. The numerical integration algorithm has an impact on the processed signal amplitude and phase as well, i.e., the integrator acts as a low pass filter.

3) Any offset (bias) in the acceleration signals is strongly amplified by the two numerical integration steps. Therefore, a high numerical integration error may result which increases continuously with any new evaluated data sample.

4) In general, any single integration step requires an initial integration condition. In case of missing or imprecise initial conditions a high numerical integration error may evolve.

In this project, the most critical points are 3) and 4), i.e., the quality of the recalculated displacement signal is strongly correlated to the numerical integration error caused by a signal drift of the acceleration data and by missing initial integration conditions. Both effects can be considerably mitigated by a suitable high pass filter concept which is described in more detail in what follows.

By performing (double) integration there is a strong need for digital filtering. Here, filtering means a frequency depending process which accentuates certain bands of frequencies while diminishing others. Generally, two different kinds of digital filter routines can be distinguished:

The Finite Impulse Response (FIR) filter utilises the past N data samples to calculate the filtered signal. Here, N represents the order of the applied filter. To ensure a sharp separation between the desired and undesired frequency ranges the order of the FIR filter has to be high. A high order FIR filter, however, causes a strong shift in position (similar to a delay in time) between the unfiltered and filtered signal which may contradict a succeeding failure location.

On the other side, the Infinite Impulse Response (IIR) filters determine the filtered signal as a superposition of present and past data samples and past filtered signals as well. In comparison to the FIR filter the IIR filter has a reasonable frequency separation even for a low filter order, N. Unfortunately, the phase response of the IIR filter is non-linear, i.e., depending on the frequency the shift in the unfiltered and filtered signal is different. This effect may cause a serious distortion in the filtered signals and contradicts a proper comparison of a set of acceleration track data. Thus, the FIR filters as well as the IIR filters are suboptimal for the intended task of track condition monitoring.

Alternatively, a Fast Fourier Transformation (FFT) filter is applied to filter out low frequency components, e.g., data drift and unknown initial integration conditions. The essential steps of the FFT filter are:

1) To transform the actual signal into the frequency domain to get the signal specific frequency spectrum.

2) To cancel out (by zeroing) frequency components which are associated to very low frequencies, i.e., the frequency range located near the frequency of zero.

3) To retransform the modified signal from the frequency domain back into the original domain.

In doing so, a precise separation of low- and high-frequency components can be achieved while keeping the shift in the filtered data at a reasonable level.

In the overall framework of translating the acceleration data into displacement data the FFT filter is applied three times:

1) To transform the raw acceleration data to offset-free acceleration data.

2) To transform the Integrated offset-free acceleration data to offset-free integrated offset-free acceleration data.

3) To transform the double integrated offset-free acceleration data to offset-free double integrated acceleration data.

The final results of this sequential data processing framework are offset-free displacement data. They can be analysed for the purpose of failure identification and failure prediction. In detail, the displacement data are compared with thresholds given in Ril 821. Additionally, the displacement data can be processed subsequently by a band-pass filter (Butterworth filter) to fulfil the requirements given in En13848.

In summary, the presented algorithms above ensure a credible recalculation of track displacement by acceleration data which are gathered via normal operating trains. Thus, the track can be monitored more frequently without the need for special measurement trains which are expensive in money and delay time. The recalculated displacement data can be used immediately for diagnosis issues, i.e., to benchmark thresholds given in Ril821 and En13848, respectively. For the purpose of failure prediction, however, additional effort is required and explained in more detail in the next Section.

4 Development of failure identification and prediction algorithms

To establish an efficient maintenance management system, reliable failure prediction is mandatory. Before a track failure occurs (e.g., the vertical alignment becomes critical) a precursor of this failure needs to be analysed. In more detail, the temporal developments of failure precursors are of special interest. To compare displacement data gathered at consecutive days following steps have to be implemented:

1) Potential track failures have to be identified. Displacement peaks caused by other reasons (e.g., by passing switches) have to be excluded.

2) To ensure a proper comparison of several displacement data the data sets have to be aligned first. Without alignment, a direct trend analysis of displacement data would lead to misleading inferences.

3) Moreover, after a tendency in the stored historical track displacement data becomes detectable one is also interested in failure prediction. That means, to predict possible track faults in the near future and to incorporate this information in an optimally scheduled maintenance strategy. Concerning this, an appropriated mathematical model has to be selected and parameterised as well.

The very details of the above items are addressed in the next Subsections.

4.1 Identification of failures and failure positions

Before the progress in failure track precursors can be analysed the corresponding peaks in the recalculated displacement data have to be identified. Therefore, the displacement data are pre-processed via the Highpass-D0-Filter. Subsequently, amplitude peaks in the filtered displacement data are categorised according to:

a) Peaks associated with failure precursors (failure peaks) and

b) Peaks associated with switches (switch peaks).

Here, failure peaks are of special interest in the field of parameter-driven maintenance. Switch peaks, however, can be determined using given switch position information and are cancelled out subsequently, see Figure 12 for illustration.

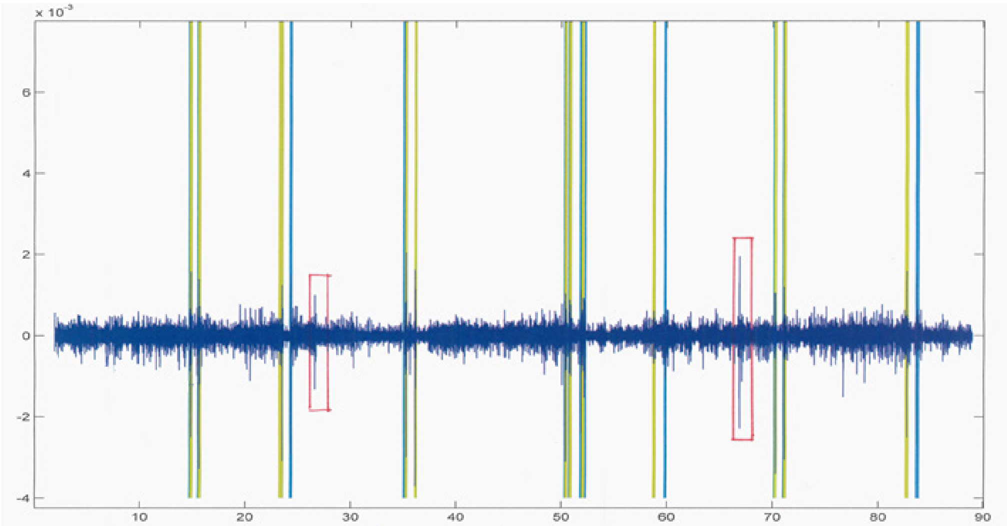

Figure 12: Calculated and D0-filtered displacement data are utilized for a first localization of potential track faults. Here the x-axes represent the track kilometres. The vertical lines indicate displacement peaks which are caused by switch crossing. (Yellow: switch in facing direction. Blue: switch in trailing direction.)

Once, the potential failures position was determined, a detailed analysis of this track section can be performed, by separating the measurement data at the according position in the entire available data streams. In doing so, not only the screening of this track section can be performed, but also the tracks behaviour and development over time. See Figure 13 for illustration of a 30m track section being cut out of the whole data stream of 90km length in 13 different days. Each colour represents another day. Unfortunately, to enable comparison on data streams of different days, additional effort has to be spent on data preparation as described in the following.

4.2 Correlation of measurements from different runs

The gathered acceleration data are labelled with track kilometre points which are not very precise due to the inherent uncertainty of standard GPS data. Thus, alignment of the recalculated displacement data is required prior to any trend analysis. Without alignment, a direct analysis of displacement data may lead to misleading inferences. With the given data set a linear approach of position correction seems to be sufficient. That is, starting with a reference displacement signal any data sample of a succeeding displacement signal (the query) is shifted by the same amount in position. The actual amount of this linear shift is determined by maximising the associated cross-correlation of the reference signal and the query. Figure 13 displays the problem of not well overlapping data streams. It is obvious, that comparability of the data streams can only be reached, when the streams overlap as good as possible to overcome the shift in phase, seen along the x-axis. While the algorithms are intended to be run unattached and as self-sufficient as possible, introducing the next data preparation step supports the algorithms stability and robustness.

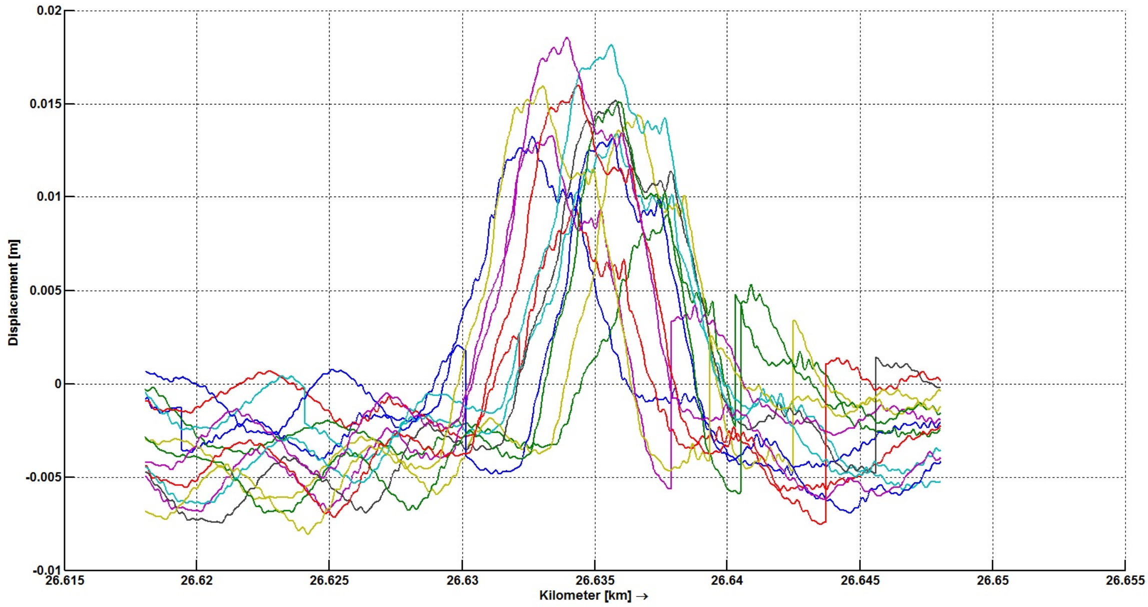

Figure 13: Example of an isolated defect around km 26,635. Each color represent a different measurement run from a different day.

To overcome this problem, several mathematical methods are available. In this project a squared distance function was defined, to compare the data streams as well as the corresponding cross-correlation. Two different methods were chosen to ensure validation between them. Figure 14 shows a screenshot from the actual Matlab processing and has to be read as follows. The top subgraph displays a reference data stream (blue) being compared to all the others from the different days (red), each one at a time. The red curve gets shifted point wise along the x-axis from right to left subsequently. After each shift, the squared distance and cross-correlation between the two streams is derived. This leads to two function squaredDist(x) and corr(x) where x is the number of data points, the red curve was shifted from right to left. Subgraphs “Squared Distance” (left, middle) and “Correlation” (right, middle) show the graphs of these functions. However, the squared distance needs to be minimized, while the cross-correlation has to be maximized to find the number of data points x, where the blue and the red curve best overlap. These maximum and minimum points are highlighted in both graphs by a red marker. The number next to the marker is the corresponding x value of the minimum and maximum respectively.

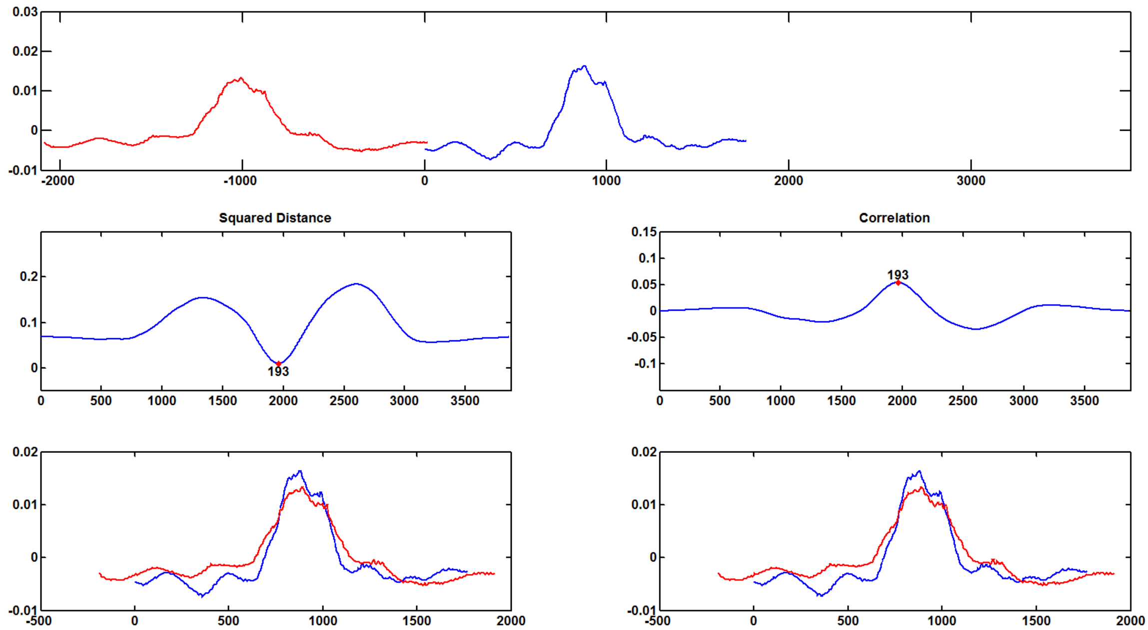

Figure 14: Data processing of two measurement streams, calculating the squared distance function (left, middle) and the cross-correlation (right, middle)

Here both, functions derive x as 193, which is interpreted as the number of data point, the original red curve needs to be shifted along the x-axis to best fit to the blue one. Note that positive x turns into a left-shift, while negative values lead to right-shifts. The remaining two subgraphs in the bottom row, display the resulting scene when shifting the original red curve by x with respect to the one and the other function. In this figure, both functions compute the same value of 193 therefore, both subgraphs are identical. After this procedure the measurement streams are best prepared to be analysed for prognostic and prediction manners. In contrast to Figure 13 the result can be found in Figure 15.

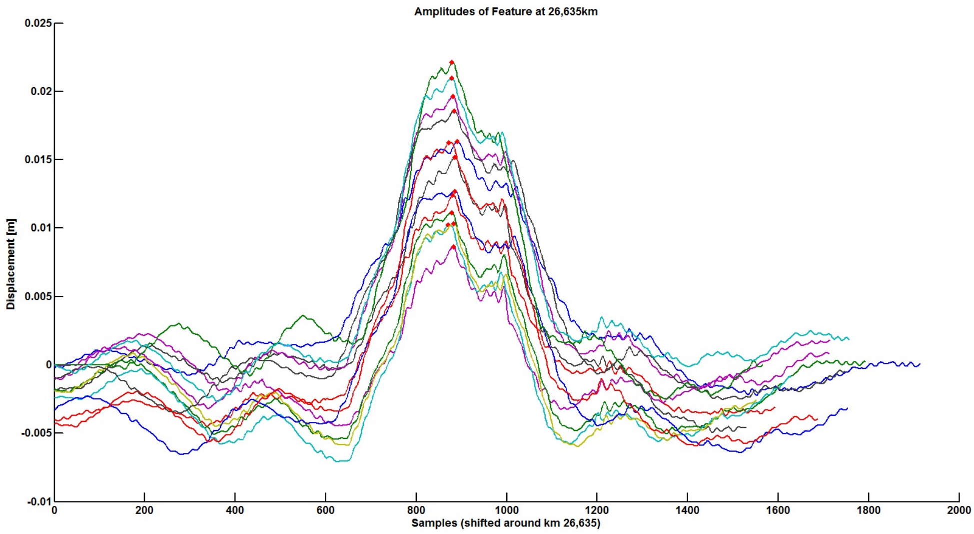

Figure 15: Resulting measurement data, after correlation precedure of isolated defect around km 26,635

Now, as the data streams of the identified potential failure position are extracted and correlated, the criticality of this failure – according to the national and European regulations here expressed in the absolute value of the displacements amplitude – needs to be determined and transferred into a time series to get the tracks deterioration. In anticipation of the algorithm described in the following, Figure 15 already highlights the amplitudes (red markers) found by the algorithm.

4.3 Amplitude mapping and time series analysis

The first step, to ensure a robust benchmark of signals even in the case of multi-amplitudes the query signal is multiplied with a smoothing window function (similar to a Gaussian-bell curve). Thus, the query signal in the near of the reference amplitude is unchanged whereas distant peaks are mitigated. Hence, the likelihood of a miss-mapping of local peaks in the displacement data can be reduced significantly.

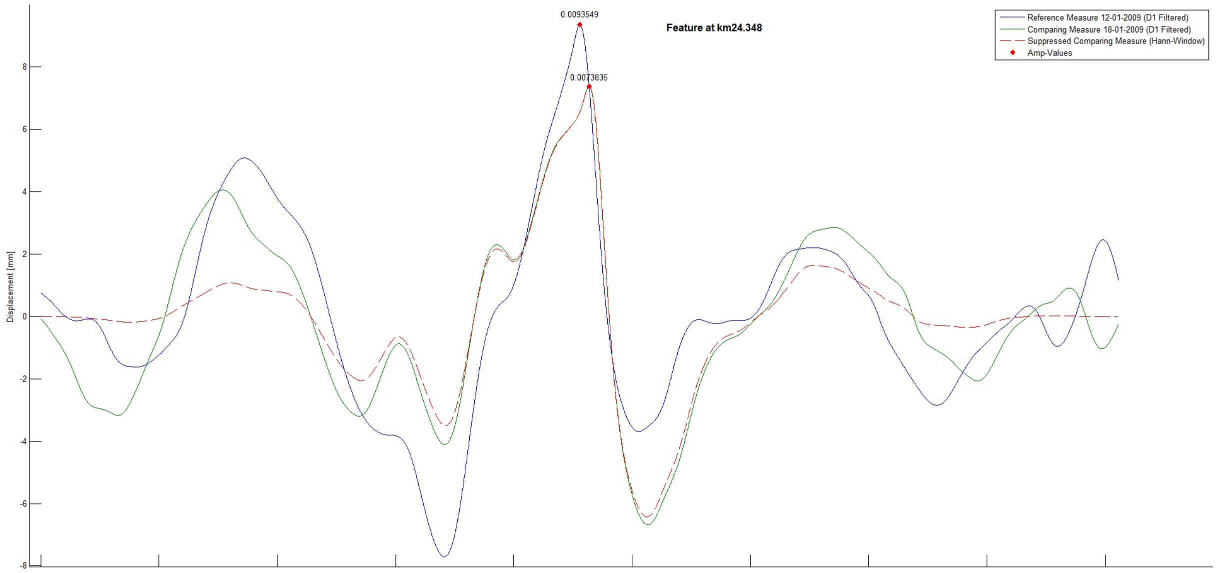

Figure 16: Finding the right amplitude in the comparing vector (green) by multiplying with a bell curve (result in red) and find amplitude in red curve. Now amplitude of reference vector (blue) and comparing vector (green) can be found and compared.

Finally, the correctly mapped displacement peaks are stored and used for a failure trend analysis. See Figure 17 and Figure 18 for illustration. Figure 17 displays 30m pieces of displacement data around km 26,635, while in Figure 18 the temporal development of their amplitudes is respected. The identified amplitudes marked in red in Figure 17, can be rediscovered in Figure 18 as blue markers.

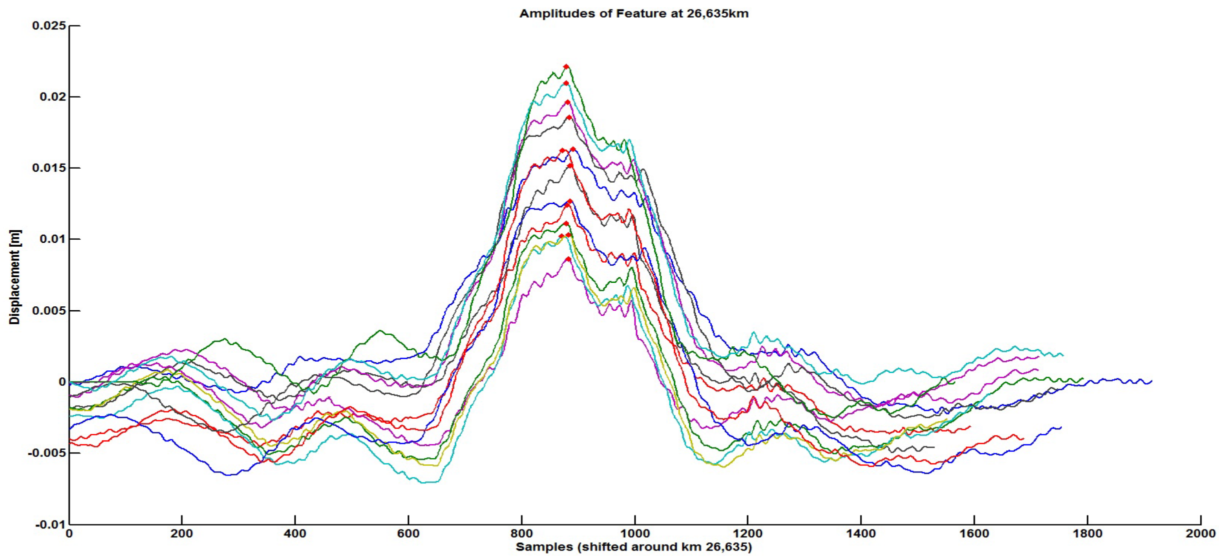

Figure 17: The development of a displacement peak in the near of track kilometer 26,635.

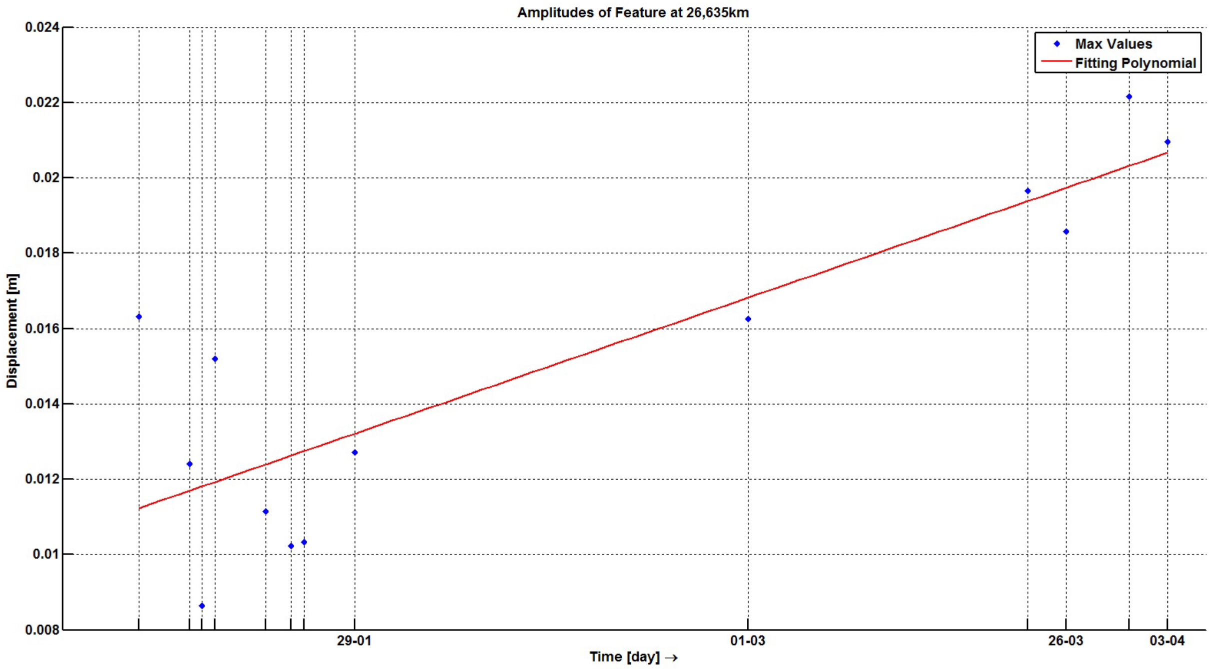

Figure 18: Trend analysis of amplitudes corresponding to track section around km 26,635

As Figure 18 most impressive shows, the track defect found at km 26,635 deteriorates over time. The given regression line's slope can generally be interpreted as deterioration rate. But while measurement uncertainties haven't been considered so far, confidence intervals have to be derived to create reliable information. This among others is described in more detail in the next section.

Finally, in accordance to the trend analysis shown in Figure 18, the missing values over time can be interpolated. For instance, there is no measurement information given for the month of February. Figure 19 offers another visualization of the same track segment, while the missing values have been interpolated. While the colour indicates the vertical displacement in [mm], the failures growth can easily be seen along the time on the y-axis in days.

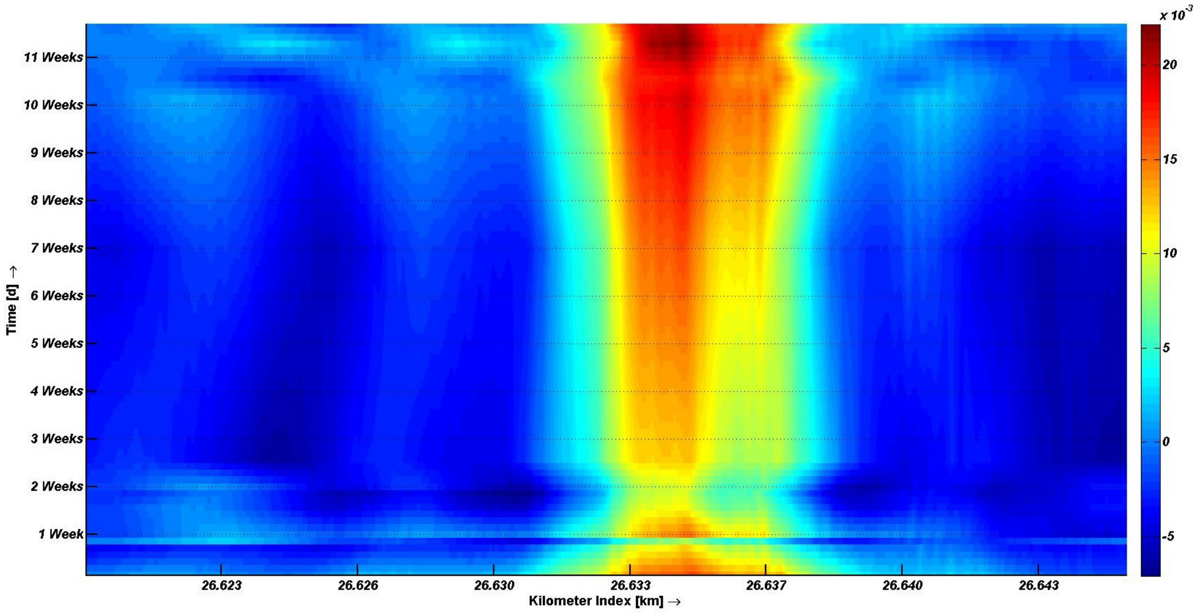

Figure 19: Track section at km 26,635. The colour indicates the vertical displacement of the track in [mm]

4.4 Prognosis and failure prediction model

In the previous Sections it has been described 1) how specific track failures are detected, 2) how several measurement data sets for the same track kilometres become comparable, and 3) how the associated peaks in the displacement data are gathered. In case, that none of the previous identified displacement peaks did cross a threshold given in Ril821 and EN13848, respectively, the prediction of track failure becomes of high interest for an efficient maintenance strategy.

Most degradation processes evolve linearly in time – at least in the near future. Therefore, the stored information of the displacement peaks is used to calibrate a linear regression model. In detail, the two parameters of a regression line, the intercept- and the slope-parameter, are modified by minimising the differences between the regression line and the displacement peaks gathered at different time points but at the same track position. Once calibrated the resulting linear regression model can be utilized to make some failure prediction. For the given example of track section at km 26,635 in Figure 18, the linear regression model is introduced as red line. In more detail, by knowing the intercept value and the associated slope of the regression line the remaining time until the regression line crosses one of the thresholds given in Ril821 and EN13848, respectively, can be determined analytically. By quantifying this time window, the maintenance tasks become optimally schedulable while reducing sudden system failures and additional costs.

Up to this point measurement imperfections and resulting uncertainties of the failure prediction have been neglected but may have a serious impact on the quality of the overall data-driven maintenance concept. In general, any measurement data are discrete in time and are corrupted by measurement noise additively. Subsequently, this measurement uncertainty is propagated to the determined displacement peak records and to the parameters of the regression line, too. That is, the determined quantities should be treated as random variables but not as single scalar values. In consequence, the resulting outcome of the linear regression model as well as the time points indicating a violation of threshold limits (Ril821 or En13838) have to be considered as random variables. Thus, the remaining time for calculated track maintenance tasks should be given as associated confidence intervals instead of single scalar quantities. The mapping of the measurement uncertainty up to the outcome of the linear regression model is state of the art in uncertainty analysis. Local sensitivities (Fisher Information Matrix) in conjunction with the Cramer-Raó inequality provide the desired uncertainty information, see Figure 20 for illustration. In case of the predicted time points of threshold crossing, however, the propagation of the uncertainty is non-linear. To ensure reasonable confidence intervals of these time points sophisticated uncertainty propagation algorithms have to be applied. In consequence, non-symmetric confidence intervals of the predicted time points are derived.

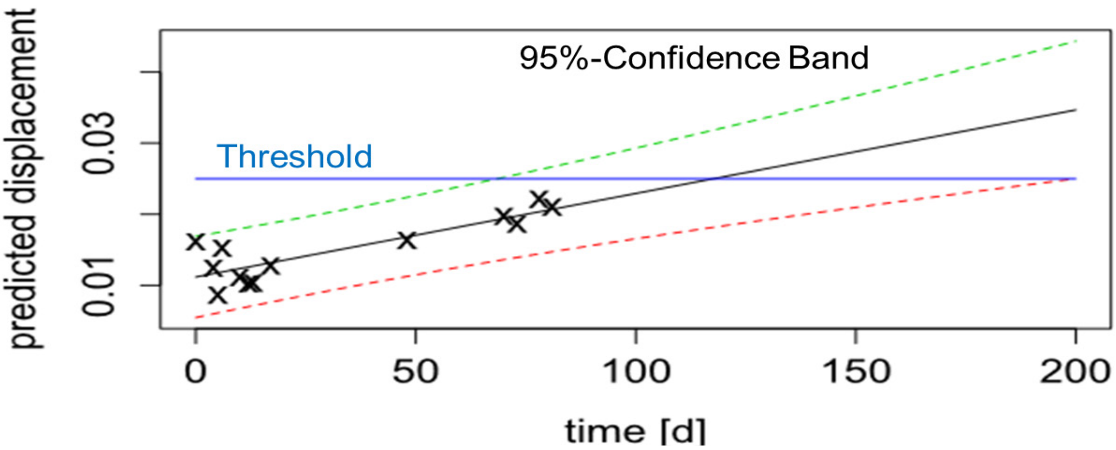

Figure 20: For the purpose of track failure prediction a linear regression line is used. To account for measurement imperfection the associated confidence band is illustrated as well.

5 Man Machine Interface

To guarantee an easy exchange of information the determined quantities have to be stored in so-called railML-files. For this purpose, a XML parser is utilised to transfer the calculated results into proper railML format files automatically. That is, in subsequent steps, e.g., scheduling of maintenance tasks, the quantities of interest can be used without any additional effort of format setting. The work was done in the project is described in Del. 3.2.

6 Conclusions

6.1 Key Findings & Development

The developed laser measuring system combined with the new assessment algorithms show their suitability in the demonstrator Munich, Nurnberg, Ingolstadt and Rosenheim. The Life-Cycle-Analysis underlines the economics of the necessary investments.

The algorithms derived in WP 3.1 ensure a proper processing of acceleration data gathered by commercial trains for the purpose of an efficient track monitoring. Here, the most critical issue is to eliminate artefacts, i.e., sensor drift and integration error, which affect the recalculated displacement data seriously. It is demonstrated that the Fast Fourier Transformation concept and the zeroing of the low frequency range diminish these artefacts considerably. Subsequently, the resulting displacement data are analysed for potential track failures. Therefore, any peak in the displacement data is detected. Peaks which can be associated with switches are cancelled out while the remaining displacement peaks are stored and compared with predefined threshold values given in Ril821 and En13838, respectively. It is also shown, how data records are analysed to detect displacement peaks associated with the same track kilometre. Subsequently, data gathered at consecutive days are used for the purpose of failure prediction. To overcome the non-avoidable distortion in the track position of succeeding data sets the considered displacement data are aligned in relation to a reference signal. An additional smoothing step ensures a credible comparison of displacement peaks of succeeding measurement re-runs. Thus, the development in the displacement peaks becomes detectable and can be applied to calibrate an associated linear regression model. In detail, the regression model enables a prediction of future track failures and can be used for an optimal maintenance concept additionally. To make this process robust against measurement imperfections, measurement uncertainty is addressed explicitly. Thus, all determined quantities are described by random numbers instead of single scalar values.

In summary, the overall data processing framework enables an efficient track monitoring strategy while keeping the computational load low. All derived inferences are stored in a format of railML which guarantees a standardised exchange of information to third parties.

6.2 Remaining Challenges

The migration of an innovation is a long, time consuming process. The basic inspection rules have to be adjusted for loaded measurements in switches, an acceptance of the railway authority in necessary.

The number of required measurement cars and an inspection plan for the largest stations in the DB network has to be developed. The next technical step is the automated integration of the data into the DB Inspection Database *IIS*.
During these migration steps, the technical focus will be the development of advanced monitoring technologies in switches, especially for the signalling part.

Similar advanced monitoring technologies has to be developed for the straight track, focused on monitoring under severe weather conditions and natural disasters.

The overall framework of the recalculation of displacement data as well as the track failure prediction has to be validated with highly precise reference data recorded by a measurement train. It is expected that there is a need for an additional fine tuning of the applied algorithms. It should be stressed, however, that the general framework of data processing will be unchanged in this case. In general, the tuning parameters can be modified computationally by minimising the differences between highly precise reference data and the recalculated displacement data gathered by commercial trains.